AD-751 264

HAZE-FREE AND CLOUD-FREE LINES-OF-SIGHT THROUGH THE ATMOSPHERE

Iver A. Lund

Air Force Cambridge Research Laboratories
L. G. Hanscom Field, Massachusetts

13 September 1972

AIR FORCE CAMBRIDGE RESEARCH LABORATORIES

L. G. HANSCOM FIELD, BEDFORD, MASSACHUSETTS

Haze-Free and Cloud-Free Lines-of-Sight Through the Atmosphere

IVER A. LUND

D D C

NOV 15 1972

D

AIR FORCE SYSTEMS COMMAND

United States Air Force

Qualified requestors may obtain additional copies from the Defense Documentation Center. All others should apply to the National Technical Information Service.

DOCUMENT CONTROL DATA - R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author)	2a. REPORT SECURITY CLASSIFICATION
Air Force Cambridge Research Laboratories (LKI) L. G. Hanscom Field Bedford, Massachusetts 01730	Unclassified
	2b. GROUP

3. REPORT TITLE

HAZE-FREE AND CLOUD-FREE LINES-OF-SIGHT THROUGH THE
ATMOSPHERE

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)
Scientific.   Interim.

5. AUTHOR(S) (First name, middle initial, last name)

Iver A. Lund

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
13 September 1972	20	15

8a. CONTRACT OR GRANT NO.	9a. ORIGINATOR'S REPORT NUMBER(S)
b. PROJECT, TASK, WORK UNIT NOS. 8624-02	AFCRL-72-0540
c. DOD ELEMENT 62101F	9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)
d. DOD SUBELEMENT 681000	ERP 413

10. DISTRIBUTION STATEMENT
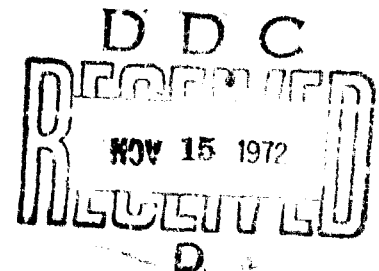
Approved for public release; distribution unlimited.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
TECH, OTHER	Air Force Cambridge Research Laboratories (LKI) L. G. Hanscom Field Bedford, Massachusetts 01730

13. ABSTRACT

    Clear and cloud-free line-of-sight probabilities have been derived from
analysis of: (1) Whole-sky photographs, (2) visual sky cover observations,
(3) jointly observed sky cover and sunshine, (4) satellite observations and
(5) in-flight observations. The most accurate probabilities of cloud-free lines-
of-sight through the entire atmosphere can be obtained from a model derived
from several thousand whole-sky photographs and visual sky cover observations.
The most accurate probabilities of both cloud-free and haze-free conditions
through the entire atmosphere, or portions of the atmosphere, can be obtained
from the in-flight observations.

DD FORM 1473
1 NOV 68

Under the setup

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Clouds						
Haze						
Seeing						
Lines-of-sight						
Optical seeing						
Infrared seeing						
Whole-sky photographs						
Sky cover						
In-flight observations						

AIR FORCE CAMBRIDGE RESEARCH LABORATORIES

L. G. HANSCOM FIELD, BEDFORD, MASSACHUSETTS

Haze-Free and Cloud-Free Lines-of-Sight Through the Atmosphere

IVER A. LUND

AIR FORCE SYSTEMS COMMAND

United States Air Force

iii

Abstract

Clear and cloud-free line-of-sight probabilities have been derived from analysis of: (1) Whole-sky photographs, (2) visual sky cover observations (3) jointly observed sky cover and sunshine, (4) satellite observations and (5) in-flight observations. The most accurate probabilities of cloud-free lines-of-sight through the entire atmosphere can be obtained from a model derived from several thousand whole-sky photographs and visual sky cover observations. The most accurate probabilities of both cloud-free and haze-free conditions through the entire atmosphere, or portions of the atmosphere, can be obtained from the in-flight observations.

Contents

Illustrations

Haze-Free and Cloud-Free Lines-of-Sight Through the Atmosphere

1. INTRODUCTION

Estimates of the probability of clear lines-of-sight through the atmosphere are required in design for determining the utility of optical and infrared communications, search and tracking systems. These estimates are also required in operational planning for visual bombing and reconnaissance. Before the required probabilities can be estimated accurately, it is extremely important to know how a clear line-of-sight is defined.

For infrared transmission, clear can usually be defined as cloud-free; for visual wave lengths, clear must be defined as both cloud-free and haze-free.

Clear line-of-sight probabilities have been derived from analysis of:
(1) Whole-sky photographs, (2) visual sky cover observations, (3) jointly observed sky cover and sunshine, (4) satellite observations, and (5) in-flight observations.

2. PROBABILITIES FROM WHOLE-SKY PHOTOGRAPHS

Whole-sky photographs were obtained by the University of Missouri for the purpose of relating clear lines-of-sight to routinely observed weather elements. A Nikon F camera with a 180 degree (fisheye) lens was installed at the National

Weather Service observing site at the airport in Columbia, Missouri. Using 35 mm infrared film, high-contrast photographs of the whole-sky were taken every daylight hour, synoptic with the National Weather Service's observations, for a period of more than three years. Studies based on these observations are described by Pochop and Shanklin (1966), Bundy (1969), Shanklin (1971), Lund and Shanklin (1972a, 1972b), and Lund (1972).

Figure 1 shows the camera installation. It is on the same roof from which the National Weather Service observations are taken. The surrounding terrain is relatively flat.

A typical whole-sky photograph is shown in reduced scale in Figure 2. Usually there is good contrast between the cloudy and cloud-free areas; there are times, however, when it is difficult to distinguish clouds near the sunshield and to distinguish between clouds and haze overhead.

Figure 3 depicts the template that was used to determine azimuth and elevation angles. The template was placed over each photograph. Two students independently examined the center of each of the 33 circles for the presence of clouds. These 33 lines-of-sight were recorded as either cloudy or cloud-free. (Most of the haze conditions were included among the cloud-free cases since the infrared wave lengths penetrate most haze.)

Photographs and supporting National Weather Service observations for the hours of 0900, 1200 and 1500 LST for a period of more than three years (March 1966 through September 1969) were collectively examined, and the relative frequency of a cloud-free line-of-sight was found for each elevation angle as a function of the tenths of cloudiness reported by the National Weather Service. Figure 4 depicts relative frequencies of cloud-free lines-of-sight (CFLOS), as a function of elevation angle and total sky cover, as determined from the photographs. The curves are shown without any smoothing. The relative frequencies consistently increase with decreasing cloudiness. With but few exceptions, probabilities of CFLOS increase as the zenith angle is approached. Failure to increase consistently is likely due to minor sampling instabilities.

Figure 5 is a subjective smoothing of Figure 4. It is believed that these curves represent the most accurate probabilities of CFLOS as a function of elevation angle and total sky cover currently available. It shows for example, that at an elevation angle of 40° there is approximately a 0.99 probability of CFLOS when the weather observer reports a clear sky (0 tenths), a 0.95 probability of CFLOS when the weather observer reports 1/10 sky cover ..., a 0.27 probability of CFLOS when the weather observer reports 9/10 sky cover, and a 0.07 probability of CFLOS when the weather observer reports 10/10 cover.
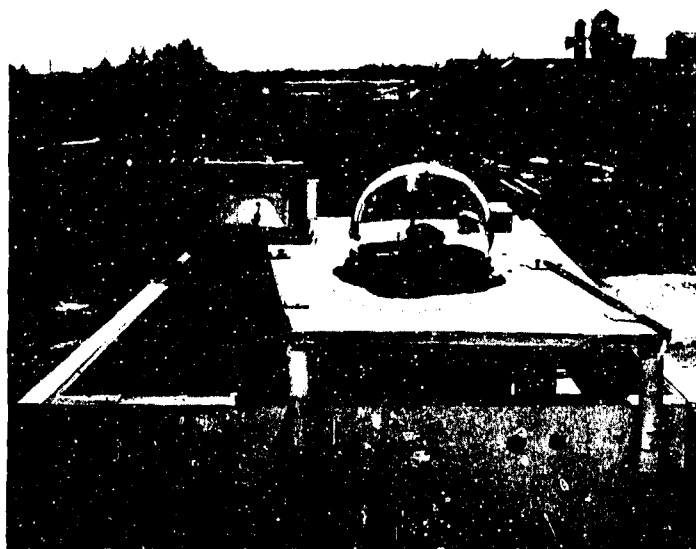
Figure 1. An Overall View of the Nikon F Whole-Sky Camera, Sunshield, and Glass Dome (Bundy, 1969)
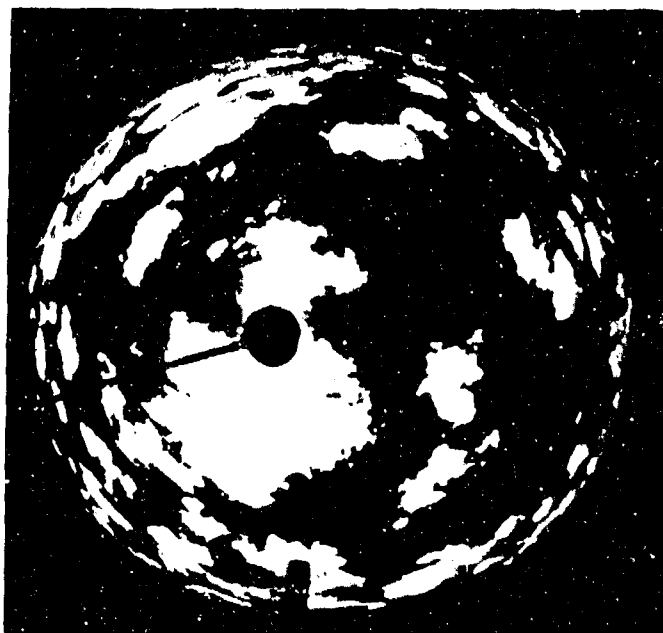

Figure 2. An Example of a Whole-Sky Photograph

4

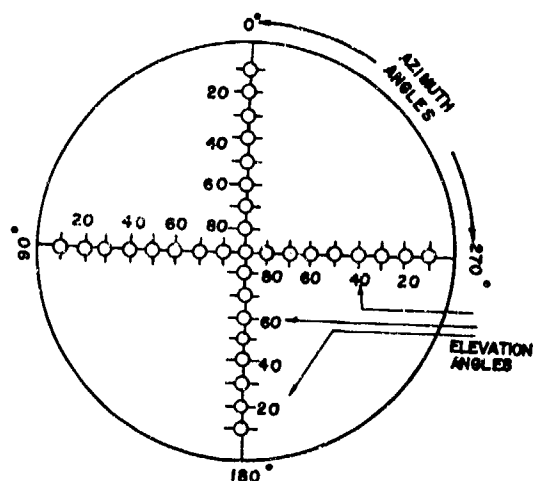Figure 3. Template Used to Determine
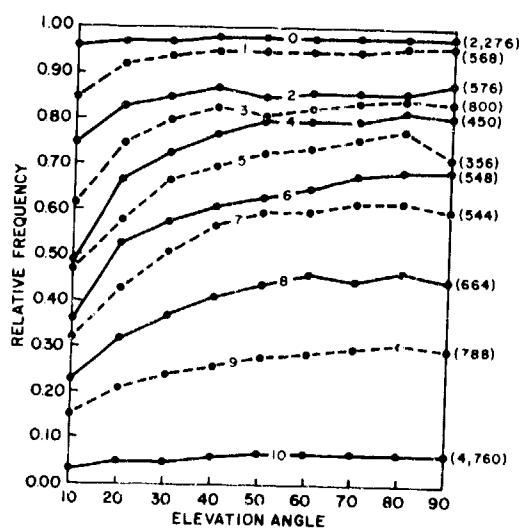Azimuth and Elevation Angles (Bundy, 1969)

Figure 4. Relative Frequencies of
CFLOS as a Function of Elevation Angle
and Observed Total Sky Cover in Tenths
(without smoothing). Each point is based
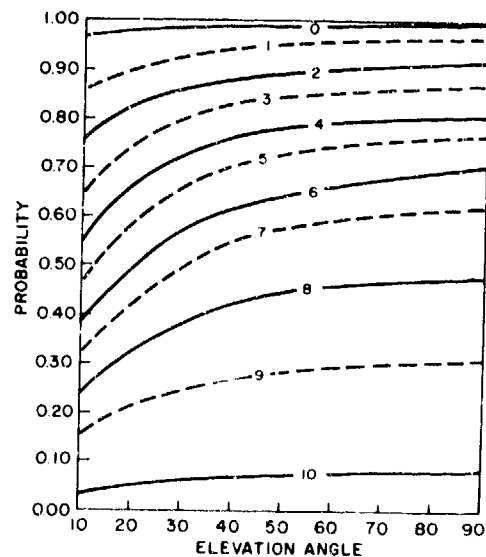on the number of observations shown at
the end of the line

Figure 5. Probabilities of CFLOS as
a Function of Elevation Angle and
Observed Total Sky Cover, in Tenths

Probabilities of CFLOS can be estimated through the use of the following formula:

$$_\alpha\hat{P}_1 = {}_\alpha C_s K_1 \tag{1}$$

where $_\alpha\hat{P}_1$ is a column vector of α rows, one row for each angle considered; $_\alpha C_s$ is a matrix for α rows and s columns, one row for each elevation angle, one column for each sky cover category; and $_s K_1$ is a column vector of s rows. The $\hat{P}$ values are estimates of probabilities of CFLOS through the atmosphere: the C values are probabilities of CFLOS at angles α given k tenths of cloudiness, and the k values are probabilities of each k tenths of cloudiness.

The $_\alpha C_s$ matrix is contained in Table 1. The values were extracted from Figure 5.

Table 1. Probabilities of CFLOS as a Function of Elevation Angle and Observed Total Sky Cover.

Elevation Angle (deg)	Sky Cover (Tenths)										
	0	1	2	3	4	5	6	7	8	9	10
90	1.00	.97	.92	.87	.81	.77	.70	.62	.48	.31	.08
80	.99	.97	.92	.87	.81	.77	.69	.61	.47	.31	.08
70	.99	.97	.91	.86	.80	.76	.68	.61	.47	.30	.08
60	.99	.96	.90	.85	.80	.75	.66	.60	.46	.29	.08
50	.99	.96	.90	.85	.78	.73	.64	.58	.45	.29	.08
40	.99	.95	.88	.83	.76	.71	.62	.55	.42	.27	.07
30	.98	.93	.86	.80	.73	.66	.57	.50	.38	.24	.06
20	.98	.90	.83	.75	.67	.59	.50	.42	.33	.21	.05
10	.97	.86	.76	.65	.55	.47	.39	.32	.24	.16	.03

As an example of the use of Eq. (1), let us assume that we wish to estimate unconditional (climatic) probabilities of CFLOS for Columbia, Missouri. From the historical records available for Columbia, Missouri, we obtained the following probabilities of 0/10, 1/10, ..., 9/10, 10/10 sky cover: .187, .047, .047, .049, .037, .031, .045, .045, .055, .065, and .392 respectively.

$$\alpha \hat{P}_1 = \begin{pmatrix} 1.00 & .97 & \cdots & .31 & .08 \\ \cdot & \cdot & & \cdot\cdot & \cdot \\ \cdot & \cdot & & \cdot & \cdot \\ \cdot & \cdot & & \cdot & \cdot \\ \cdot & \cdot & & \cdot & \cdot \\ \cdot & \cdot & & \cdot & \cdot \\ \cdot & \cdot & & \cdot & \cdot \\ \cdot & \cdot & & \cdot & \cdot \\ .97 & .86 & \cdots & .16 & .03 \end{pmatrix} \begin{pmatrix} .187 \\ .047 \\ \cdot \\ \cdot \\ \cdot \\ \cdot \\ \cdot \\ .065 \\ .392 \end{pmatrix} = \begin{pmatrix} .509 \\ .506 \\ .504 \\ .500 \\ .496 \\ .483 \\ .463 \\ .437 \\ .392 \end{pmatrix} \qquad (2)$$

The relative frequencies of CFLOS actually observed at Columbia, Missouri were .492, .497, .493, .489, .485, .476, .457, .437, and .382. The small differences between the values obtained by solving Eq. (1) and those obtained from the observational data are due to the smoothing of curves in Figure 4 to obtain Figure 5. This comparison is an illustration of the use of Eq. (1) and not an independent test of the equation. Data are not currently available to perform an independent test.

We have also used the data extracted from the whole-sky photographs to study the persistence and recurrence of CFLOS (Lund and Shanklin, 1972a) and to study CFLOS as a function of cloud type (Lund and Shanklin, 1972b).

3. PROBABILITIES FROM SKY COVER OBSERVATIONS

Methods for estimating line-of-sight probabilities from available meteorological observations of sky cover have been developed by Blackmer and Harllee (1960), Fox (1961), Appleman (1962), Lund (1965, 1966), and others. These methods often do not take into account the angle of view through the atmosphere, or the fact that observers see the sides of clouds as well as their bases when they estimate sky cover, tending to overestimate total earth cover. It has been difficult to determine how accurately these methods estimate true probabilities because the true probabilities are not accurately known. If true probabilities can be obtained from photographs, or in-flight observations, they can be related to sky cover with expressions such as Eq. (1).

4. PROBABILITIES FROM SKY COVER AND SUNSHINE OBSERVATIONS

Long records of sunshine and sky cover observations were used by Lund (1965, 1966) and McCabe (1965) to estimate probabilities of clear lines-of-sight through the atmosphere. Lund (1966) devoted most of the introduction of his

article to explaining how a "clear" line-of-sight was defined for his study. He stated that:

"A clear line-of-sight is defined as one which permits sufficient bright sunshine (radiation) to pass through the atmosphere to activate the sunshine recorder. Presumably such a condition would also permit sensing a signal through the atmosphere with an optical or infrared detector. The path length is the distance from the top of the atmosphere to the surface of the earth. Since the sunshine recorder does not detect 'thin' clouds, the probability of a clear line-of-sight, as defined in this paper, exceeds the probability of a cloud-free line-of-sight by an amount equal to the probability of 'thin' clouds, roughly 6 to 20 percent at the stations under study."

In earlier articles by McCabe (1965) and Lund (1965), it is also pointed out that clear does not always mean cloud-free. McCabe (1965) states:

"It is known that sunshine recorders often record the occurrence of 'bright sunshine' through thin clouds, especially at high sun angles."

These statements have been frequently overlooked by users of the graphs and equations developed by McCabe and Lund.

5. PROBABILITIES FROM SATELLITE OBSERVATIONS

Satellite technology has not developed to the point where it is feasible to use the observations to obtain precise estimates of the probability of clear, or cloud-free, lines-of-sight as a function of the viewing angle. They are sufficiently accurate, however, to provide some information on total cloud cover (Larson, 1971) and cloud type (Greaves and Sherr, 1970). Models developed through the use of whole-sky photographs, in-flight observations, and sunshine observations might be used to relate satellite observations of cloud cover and cloud type to line-of-sight probabilities through the entire atmosphere, but such studies are not yet available.

6. PROBABILITIES FROM IN-FLIGHT OBSERVATIONS

With the exception of a part of the work of McCabe (1965), which was based upon a set of aircraft cloud layer reports, the preceding studies pertain to seeing through the entire atmosphere. Only the collection by aircraft crews of in-flight line-of-sight observations along specific angles will provide data for estimating probabilities of clear, cloudy, or hazy lines-of-sight between flight levels and the surface, and flight levels and space. The USAF, assisted by the U.S. Navy,

Royal Air Force and some commercial airlines, is currently conducting a program (Bertoni, 1967) to collect in-flight observations. With sufficient in-flight observations, accurate line-of-sight probabilities from any aircraft altitude to the ground or sky will be obtainable for many practical problems. It is also possible to infer probabilities between levels from climatologies of such in-flight observations.

To date an insufficient number of observations has been obtained from the in-flight program to provide statistically stable estimates of line-of-sight probabilities over finite areas, altitudes, and seasons. There are, however, sufficient observations available for much of the Northern Hemisphere to prepare provisional estimates. For example, Figure 6 depicts the relative frequency of seeing the ground at 30- and 60-degree depression angles when flying in the vicinity (within five latitude and five longitude degrees) of Columbia, Missouri. The number of observations are tabulated along the right-hand margin of the figure. There were 899 observations taken from altitudes between 35,000 and 45,000 ft, 1140 observations taken from altitudes between 25,000 and 35,000 ft, ..., and only 104 observations
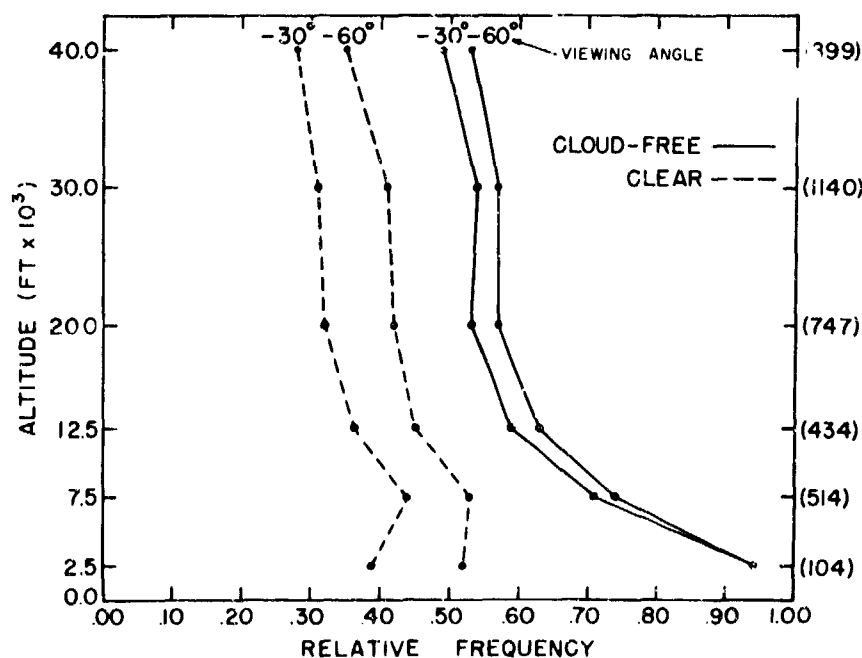

Figure 6. Relative Frequencies of Clear, or Cloud-Free, Lines-of-Sight, Observed in the Area Between 34° to 43°N and 88° to 97°W, as a Function of Altitude. The number of observations is shown in parentheses on the right hand margin

taken below 5,000 ft. The in-flight observers reported seeing the ground 28 and 35 percent of the time at depression angles of 30° and 60°, respectively, from the highest altitudes, approximately 40,000 ft. Observers flying at the next lower layer, 25,000 to 35,000 ft, reported seeing the ground at -30° three percent more frequently than from 40,000 ft, and -60° six percent more frequently. With the exception of the points on the curves at 2,500 ft, which are based on only 104 observations, the curves appear to be reasonable first estimates. The relative frequency of seeing at the steeper angle of -60° always exceeds the relative frequency at -30° which is consistent with the geometry.

When the in-flight observer could not see the ground, he indicated that the line-of-sight was obstructed by either clouds, haze, or both. Frequently, haze was the only obstruction noted by the observer. By including the "haze only" cases with the clear cases, relative frequencies of CFLOS, comparable to the infrared film photographic observations, can be obtained. These are also shown in Figure 6.

The probability of a CFLOS to the ground should decrease monotonically with increasing altitude. Also, there should be a higher probability of seeing the ground at the steeper angle of -60° than at -30°. The relative frequencies satisfy these conditions with only one minor exception.

When the in-flight observation program is completed, possibly by mid-1973, sufficient data will be available to obtain accurate estimates of CFLOS probabilities over many climatologically different geographical locations.

7. DISCUSSION

The large spatial and temporal variations in cloudiness, which are found in many geographical areas, have not been discussed in this paper. However, they are very important in determining where and when optical or infrared devices, and operations requiring seeing by humans, are employed. The purpose of this paper has been to stress the need for precise definitions of what constitutes a clear line-of-sight and to review what has been done and what is being done to obtain better estimates of clear line-of-sight probabilities.

Figure 7 illustrates a wide range of probabilities of variously defined clear lines-of-sight through the entire atmosphere obtained for Columbia, Missouri, between the hours of 0900 and 1500 LST. If cloud free and also haze-free lines are required, the two points, ⓧ , obtained from inflight observations represent the required probabilities. They are (0.27) at -30° and (0.35) at -60°. These values are based on a total of 918 in-flight observations taken within 5° latitude and 5° longitude of Columbia, Missouri, from altitudes above 35,000 ft. The X's
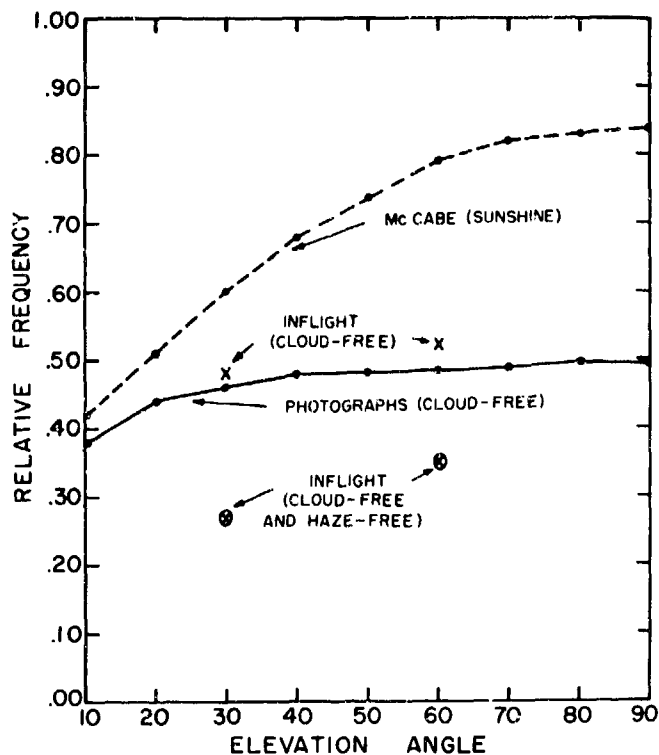
Figure 7. Relative Frequencies of CFLOS Obtained
From Whole-Sky Photographs (solid curve), and In-
Flight Observations (X's). Relative frequencies of
lines-of-sight being both cloud-free and haze free
(Ⓧ 's) and probabilities obtained from McCabe's graph
(dashed curve). Values apply to Columbia, Missouri
between the hours of 0900 and 1500 LST

shown in Figure 7, depict the percent of time observers reported clear, or haze
only. These are the cloud-free conditions. Cloud-free conditions were reported
48 percent of the time at a depression angle of 30° and 52 percent of the time at a
depression angle of 60°. The solid curve is based on an analysis of hourly whole-
sky photographs taken between 0900 and 1500 LST during a period of more than
three years, as described in Section 2 of this paper. (No smoothing was applied to
the values.)

The mean total cloud cover observed, on the 12,330 hours when whole-sky
photographs were taken, was 6.1 tenths. The dashed curve shown in Figure 7 was
obtained by entering McCabe's (1965) graph with mean total cloud cover of 61
percent. As expected, the probabilities obtained were much higher than those
obtained from the whole-sky photographs.

The curve labeled photographs in Figure 7 best represents probabilities of CFLOS over Columbia, Missouri during daytime. Probabilities estimated from the in-flight observations (X's) agree almost perfectly with estimates based on photographs. Ideally they should be slightly higher, which they were, than probabilities based on photographs, since there were occasions when there were clouds above the aircraft but no clouds on the line-of-sight below the aircraft. If the line-of-sight must be both cloud-free and haze-free, probabilities will be considerably lower, as noted by in-flight points designated ⊗. Probabilities shown along the curve labeled McCabe should be used only if the probabilities are to be used to estimate the utility of devices that can observe or transmit, through considerable amounts of clouds and haze, since these probabilities are derived on measurements obtained from sunshine recorders which can be activated under hazy and cloudy conditions.

Equation (1) and Figure 5 give the best obtainable estimates of the probability of a CFLOS through the entire atmosphere. The estimates can be found for any desired angle for most geographical locations where sky cover observations are available. (If haze constitutes an obstruction, as it would to the naked eye, these estimates would be too high. Users of Eq. (1) and Figure 5 should remember that a CFLOS is not necessarily a haze-free line-of-sight.) Requirements for modifying Figure 5 for use at locations where clouds differ markedly from Columbia, Missouri have been investigated (Lund and Shanklin, 1972b). Persistence and recurrence probabilities are being studied.

Acknowledgments

Preceding page blank

References

Appleman, H. S. (1962) A comparison of simultaneous aircraft and surface cloud observations, J. Appl. Meteorol. 1:548-551.

Bertoni, E. A. (1967) Clear lines-of-sight from aircraft, Air Force Surveys in Geophysics, No. 196, Air Force Cambridge Research Laboratories, Bedford, Massachusetts.

Blackmer, R. H., Jr. and Harllee, J. (1960) Determination of the Percent of Time the Ground is Visible From an Aircraft Flying Above Clouds, Scientific Report No. 1 under Contract AF 19(628)-7312, Stanford Research Institute, California.

Bundy, D. S. (1969) A Two Year Study of the Probability of Cloud-Free Lines-of-Sight at Columbia, Missouri, Unpublished Master's dissertation, University of Missouri, Columbia.

Fox, R. L. (1961) Sunshine-cloudiness relationships in the United States, Monthly Weather Review 89:543-548.

Greaves, J. R. and Sherr, P. E. (1970) The use of cloud-amount and cloud-type statistics in the design and operation of aerospace systems, Fourth National Conference on Aerospace Meteorology, Las Vegas, Nevada. Sponsored by American Meteorological Society and American Institute of Aeronautics and Astronautics.

Larson, P. A. (1971) Photogrammetry applied to environmental studies, George C. Marshall Space Flight Center, Research Achievements Review No. 8, Huntsville, Alabama 10 pp.

Lund, I. A. (1965) Estimating the probability of a clear line-of-sight from sunshine and cloud cover observations, J. Appl. Meteorol. 4:714-722.

Lund, I. A. (1966) Methods for estimating the probability of clear lines-of-sight, or sunshine, through the atmosphere, J. Appl. Meteorol. 5:625-630.

Lund, I. A. (1972) Clear and cloud-free lines-of-sight through the atmosphere, International Conference on Aerospace and Aeronautical Meteorology, American Meteorological Society, 45 Beacon St., Boston, Massachusetts, pp. 40-46.

Preceding page blank

Lund, I. A. and Shanklin, M. D. (1972a) Photogrammetrically determined cloud-free lines-of-sight through the atmosphere, J. Appl. Meteorol. 11:773-782.

Lund, I. A. and Shanklin, M. D. (1972b) Universal methods for estimating probabilities of cloud-free lines-of-sight through the atmosphere. Accepted for publication in the J. Appl. Meteorol.

McCabe, J. T. (1965) Estimating mean cloud and climatological probability of cloud-free lines-of-sight, Technical Report 186, Environmental Technical Applications Center, USAF, Bldg. 159, Navy Yard Annex, Washington, D. C.

Pochop, L. O. and Shanklin, M. D. (1966) Sky cover photograms, a new technique, Weatherwise 19:198-200.

Shanklin, M. D. (1971) Photogrammetrically determined cloud-free lines-of-sight at Columbia, Missouri, Final Report under Contract No. F19628-68-C-0140, Air Force Cambridge Research Laboratories, Bedford, Massachusetts.